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Published in:
Energy Efficiency

DOI (link to publication from Publisher):
10.1007/s12053-019-09818-7

Publication date:
2019

Document Version
Accepted author manuscript, peer reviewed version

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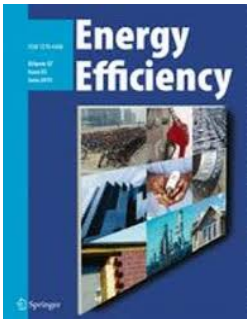
This is a post-peer-review, pre-copyedit version of an article published by Springer Nature in Energy Efficiency on 08 August 2019.



Please cite as follows:

Trotta, G. (2019). Assessing energy efficiency improvements, energy dependence, and CO 2 emissions in the European Union using a decomposition method. Energy Efficiency, 12(7), 1873-1890. doi:10.1007/s12053-019-09818-7

The final authenticated version is available online at https://link.springer.com/article/10.1007/s12053-019-09818-7

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Abstract

The achievement of the 32.5% energy efficiency target set for 2030 in the Energy Efficiency Directive 2018/2002 could determine the success of the EU Member States' actions and policy measures to improve energy efficiency. However, the way the target was set presents several limitations, and the target is based on a hypothetical percentage of future primary energy use rather than absolute energy savings. Thus, the objectives of this study are to provide new insight into (i) the levels of energy efficiency improvements achieved by the EU over the period 1995–2015 by employing a decomposition analysis approach—Logarithm Mean Divisia Index—and using disaggregated final energy consumption data, (ii) the progress of the EU towards the energy efficiency target set for 2030, and (iii) the energy security and climate benefits associated with energy efficiency improvements. The results show that from 1995 to 2015, efficiency allowed the EU to save approximately 235 Mtoe of final energy. Additionally, energy efficiency improvements reduced the EU's dependence on energy imports at the average rate of 1% per year, saved 811 $MtCO_2$, and contributed to achieving 52.5% of the energy efficiency target set for 2030.

Keywords: energy efficiency; index decomposition analysis; LMDI; European Union; energy security; carbon dioxide emissions.

1. Introduction

The European Commission's 'Clean Energy for All Europeans' package contains several measures designed to increase energy efficiency, boost renewable energy, and reform the European energy market and, provides a framework for energy policy in the European Union for the next decade (European Commission 2016a). 'Energy efficiency first' is considered the guiding principle for future energy policymaking and a key element to achieving energy transition. To provide a long-term perspective for policy plans and investments by Member States and investors, the proposal establishes a 30% energy efficiency target for 2030, which is binding at the EU level (European Commission 2016b; 2016c).

Following the Commission's proposal, numerous disputes emerged among civil society groups, businesses, lobbies, academicians, and policymakers regarding which energy efficiency target the EU should adopt for 2030. Some called for a more ambitious target, while others tried to water it down. After months of negotiations, the revised Energy Efficiency Directive (EU) 2018/2002 (11th of December 2018) established a binding 32.5% energy efficiency target for 2030 with a clause for an upward revision by 2023 (The European Parliament and the Council of the European Union 2018).

The energy efficiency target is set by using the Price-Induced Market Equilibrium System (PRIMES) model, which simulates demand and supply behaviour by agent (sector) under different assumptions regarding economic development, emissions and other policy constraints, technology changes and other drivers (PRIMES MODEL 2013-2014). However, how the target is defined and determined presents several limitations. First, the PRIMES model calculates primary and final energy savings rather than the reduction in energy use due to energy efficiency improvements. While achieving efficiency typically implies saving energy, the opposite is not necessarily true; reductions in energy consumption can be driven by several other factors, such as structural changes towards less energy-intensive industries and lower economic activity. Second, the energy efficiency target is based on a theoretical percentage of future primary energy use rather than absolute energy savings. Given the complexity of the energy system, many factors driving future energy supply and demand, such as macroeconomics, oil prices, technology improvements, and policies, may follow unexpected trajectories (E3MLab & IIASA 2016). Consequently, the actual energy supply and demand can significantly differ from the projections. Third, although the projections of energy demand, supply, and prices have been periodically updated (2009, 2013, and 2016), the energy savings for 2030 are still calculated using the 2007 PRIMES baseline projections. Thus, a portion of the 32.5% target could be achieved because of structural changes to the EU economy resulting from the recession of 2008 rather than renewed measures to reduce energy use. Additionally, the impact of the latest EU policy measures such as the Energy Performance of Buildings Directive (2010/31/EU) and the Energy Efficiency Directive (2012/27/EU), is not considered.

In contrast to previous acts of energy efficiency, in the revised Energy Efficiency Directive (EU) 2018/2002, the energy efficiency target (2007 PRIMES baseline projections) has been translated into a reduction target compared to the historical 2005 energy consumption levels. In particular, the "primary energy consumption in the Union should be reduced by 26%, and final energy consumption should be reduced by 20% compared to the 2005 levels" (The European Parliament and the Council of the European Union 2018). This comparison facilitates the assessment of the target, improves its transparency, and renders it consistent with other climate and energy targets established for 2030 (40% decrease in greenhouse gas emissions compared to the 1990 levels and at least 27% share of renewables in gross final consumption of energy).

Against this background, the aims of this study are to provide an indication of the energy savings driven by energy efficiency improvements in the European Union during the period 1995–2015 and track the progress towards the 2030 energy efficiency target by employing a decomposition analysis approach and using disaggregated final energy consumption data.

The advantage of the decomposition analysis is that it disentangles and separates variations in actual energy consumption over time into changes in economic activity, structure, and energy intensity. By isolating the changes in energy intensity (at the disaggregated level) from other factors affecting the changes in energy consumption, it is possible to estimate the amount of energy saved due to energy efficiency improvements. Then, the isolated energy efficiency improvements achieved between 2005 and 2015 are assessed against the historical 2005 final energy consumption level used as the reference year for the energy efficiency target that has been established for 2030. By tracking the energy savings due to energy efficiency improvements (alone), it is possible to obtain a clearer understanding of the actual progress of the EU towards the energy efficiency target and the remaining gap to be bridged by 2030.

Since the first oil crises of 1973–1974, most policy documents and laws regarding energy efficiency adopted by the European Union have been designed under the framework of energy security and the fight against climate change. The underlying assumption guiding these policies is that greater energy efficiency reduces energy demand and related CO_2 emissions, which, in turn, contributes to improved energy security by reducing dependence on foreign energy sources. Therefore, in the final part of the analysis, simple formulae are used to estimate the extent to which energy efficiency improvements between 1995 and 2015 translate into energy security and climate benefits. Although these economy-wide benefits of energy efficiency have been increasingly acknowledged by the European Union, they have rarely been quantified.

This study is particularly timely given the recent EU energy efficiency policy developments and the broader discussion concerning moving towards a secure and low-carbon economy. Without a proper measurement of the underlying drivers of energy consumption, it is impossible to evaluate energy efficiency improvements and some benefits at the top of the European policy agenda. Distinguishing the levels of causation driving the variation in energy consumption and the sectors/sub-sectors driving energy efficiency could provide a lever or opportunity for policies to exert influence. The results might also influence future discussions regarding the appropriate level of the energy efficiency target that should be adopted by the EU in 2030, which could strongly affect future investments and policies at the EU and national level and the achievement of the energy security and climate change goals.

The remainder of this paper is organised as follows: Section 2 provides an overview of the literature analysing energy efficiency using decomposition methods; Section 3 describes the data and empirical strategies used in this study; Section 4 illustrates the empirical results concerning energy efficiency improvements and related climate and energy security benefits; and Section 5 presents the conclusions and discusses implications for energy policies.

2. Literature review

The oil crises of 1973–1974 and the growing awareness of environmental issues have introduced energy conservation to the policy agenda. Consequently, Index Decomposition Analysis (IDA) has been developed to analyse the factors driving the changes in energy consumption and related CO_2 emissions over time to inform policy makers about trends and where to prioritise efforts.

Based on IDA, several decomposition methods including the Laspeyres method, the Paasche index, the Fischer Ideal, the Logarithmic Mean Divisia Index I (LMDI-I), and the Logarithmic Mean Divisia Index II (LMDI-II), have been developed and used in energy-related and environmental analyses over the last 40 years. Ang (2004; 2005; 2015), Ang et al. (2009), and Ang and Wang (2015) compared the different approaches to establish a broad consensus regarding the preferred method and concluded that the Logarithmic Mean Divisia Index (LMDI), especially the LMDI in the additive form (LMDI-I), is the 'best' decomposition method due to its theoretical foundation, adaptability, easy usage and result interpretation. In particular, the LMDI-I (i) passes several basic tests with good index number, (ii) provides 'perfect' decomposition, i.e. no residuals, and (iii) is easy to use as the formulae assume the same form regardless of the number of explanatory factors.

The LMDI method has gained prominence over the last several years not only among researchers (e.g., Sheinbaum et al. 2010; Shahiduzzaman and Alam, 2013; Ang 2015; Reuter et al. 2017; 2019) but also in the policy community (Braungardt et al. 2014; IEA 2015; IEA 2016a; IEA 2016b; Economidou 2017) as an effective tool for estimating energy efficiency improvements and supporting the design of energy policies.

Most academic studies employing LMDI to investigate energy-related issues are country-specific, especially in China (Ma and Stern 2008; Wu 2012; Wang et al. 2014; Xu et al. 2014; Liu et al. 2015; Carmona and Collado 2016; Xu et al. 2016; 2016; 2017), and often focus on a single sector (Mairet and Decellas 2009; Zhao et al. 2012; Nie and Kemp 2013; Achour and Belloumi 2016) with a special emphasis on the manufacturing industries (Hammond and Norman 2012; Xu et al. 2012; Ang and Xu 2013; Kim 2017; Wang and Feng 2017), but a few other studies use cross-sectoral analyses to investigate the EU overall. For example, Marrero and Ramos-Real (2013) decomposed and analysed the evolution of energy intensity in the main economic sectors in a set of EU15 countries during the 1991–2005 period. On average, the energy intensity improved in agriculture and industry but worsened in construction and services. The shift towards a service-oriented economy did not result in a more efficient use of final energy in the service sector. The authors concluded by emphasising the importance of distinguishing the components influencing global energy intensity to avoid forming misleading conclusions and improperly establishing energy policies.

Gonzalez et al. (2014) investigated the variation in the aggregate energy consumption in the EU-27 Member States during the 2001–2008 period using LMDI. The results showed that in most countries, especially the socialist states, the growing overall economic activity and the changes from less to more energy-intensive sectors were strong enough to offset the energy efficiency gains. In a subsequent study, Gonzalez (2015) applied an LMDI to explore the influence of the changes in the sectoral composition in 20 EU Member States on the aggregate energy intensity between 1995 and 2010. The results indicated that the reduction in the aggregate energy intensity was mainly driven by energy efficiency improvements (‘intensity effect’) and only partially by changes in the production structure (‘structural effect’). Particularly in Western countries, the industrial sector has been a major contributor to reducing the aggregate energy intensity; however, the service sector caused an increase in the aggregate energy intensity in most countries.

Obadi and Korček (2015) analysed the drivers of energy consumption in the EU during the pre-crisis period (2004-2008) and crisis period (2008-2012) using LMDI. By challenging the view that the decline in energy consumption was caused by the economic slowdown after 2008, the authors found that energy intensity improvements have been the most salient determining factor reducing energy consumption throughout the EU during both the pre-crisis and crisis periods.

Reuter et al. (2017) used LMDI to show the effects of both policies and autonomous developments driving the changes in primary energy consumption in some EU Member States between 2000 and 2014. The results showed that primary energy consumption decreased by 110 Mtoe from 2000 to 2014; most of this reduction was attributed to lower final energy consumption and improved efficiency in the conversion sector in a few EU Member States (UK, Germany, and Italy). More recently, Reuter et al. (2019) employed LMDI to investigate the drivers of the changes in the final energy consumption in the

European Union (complemented with an in-depth analysis of Germany and Poland) over the period from 2000-2015. Overall, efficiency improvements contributed to saving 210 Mtoe of final energy; the largest share of these efficiency gains was realised in industry, followed by the residential sector.

The contribution of this article to the previous literature is threefold. First, this study investigates the causes of the variation in the final energy consumption of the EU over a long period (1995–2015) by using disaggregated data at the sub-sector/end-use level. The disaggregation of different sectors and sub-sectors driving energy demand over a long period in this study allows for the impact of the most important acts, which have mainly been implemented during the decade 2005–2015, on energy efficiency to be better captured and provides targeted policy recommendations.

Second, in contrast to previous studies, which employed decomposition analysis to assess energy efficiency trends, in this study, the energy savings calculated with LMDI-I are used to provide a more accurate indication of the actual progress of the EU towards the energy efficiency target established for 2030.

Third, the disentangled energy savings due to energy efficiency improvements are translated into energy security and climate benefits. These results could inform policy makers regarding the wider contribution of energy efficiency to reducing CO_2 emissions and energy dependence, which is often mentioned but rarely quantified.

3. Data and methods

The dataset is composed of the final energy consumption by sector (industry, transport, residential, services, and agricultural) and sub-sector/end-use (e.g., chemical industry, cars, space heating, etc.) of the European Union. In addition, data regarding passenger and goods traffic, the number of households, the stock of dwellings permanently occupied, the floor area of dwellings, the stock of large appliances, and CO_2 emissions are collected. The primary data source is the Odyssee database (2017). The Odyssee data are complemented with data regarding the value-added and energy dependence of the European Union, which are derived from the World Bank (The World Bank, World Development Indicators

2017a; 2017b; 2017c; 2017d) and Eurostat (Eurostat 2018a) databases, respectively. The data of the European Union cover the period from 1995 to 2015. The descriptive statistics are provided in Table 1.

	Unit[1]	**N (years)**	**Mean**	**Std Dev**	**Min**	**Max**
Total gross inland energy consumption	Mtoe	21	1738.5	66.4	1607.4	1839.6
Total final energy consumption	Mtoe	21	1063.6	36.9	999.8	1115.8
Final consumption industry	Mtoe	21	309.7	26.7	263.8	334.4
Chemical	Mtoe	21	56.6	3.4	50.5	60.8
Primary metals	Mtoe	21	70.3	9.8	50.8	83
Non-metallic minerals	Mtoe	21	40.3	5.1	31.5	45.7
Wood	Mtoe	21	6.8	0.7	5.4	7.9
Paper, pulp and printing	Mtoe	21	34	2.1	30.6	38.4
Food	Mtoe	21	30.2	1.7	27.6	32.8
Textile and leather	Mtoe	21	7.9	2.6	4.4	10.8
Machinery	Mtoe	21	20.4	1	18.4	22
Transport equipment	Mtoe	21	8.7	0.8	7.4	10
Mining	Mtoe	21	24.4	4.4	17.4	30.8
Construction	Mtoe	21	3.3	0.3	2.7	3.9
Other industries	Mtoe	21	6.6	0.3	6.1	7.3
Final consumption transport	Mtoe	21	304.2	14.1	272	328.1
Passenger transport	Mtoe	21	183.9	4.9	173.4	192.2
Cars	Mtoe	21	165.9	4.1	157.5	172.6
Buses	Mtoe	21	9	0.7	7.9	10
Rail passenger transport	Mtoe	21	3.3	0.2	2.9	3.5
Domestic air transport	Mtoe	21	5.8	0.6	4.5	6.9
Passenger traffic	Gpkm	21	5519.4	289.5	4895.1	5888.6
Car traffic	Gpkm	21	4430.8	237.2	3904.4	4719.4
Road traffic via public modes	Gpkm	21	541	13.4	514.7	569.2
Rail passenger traffic	Gpkm	21	474.3	39.5	423.7	544.3
Domestic air traffic	Gpkm	21	73.3	10.2	52	88.6
Transport of goods	Mtoe	21	120.2	9.7	98.6	135.9
Trucks and light vehicles	Mtoe	21	110.0	9.8	87.7	124.6
Rail goods transport	Mtoe	21	4.1	0.5	3.3	4.9
Inland waterways transport	Mtoe	21	6	0.9	4.2	7.4
Traffic of goods	Gtkm	21	2183.3	211.8	1798.9	2522.5
Road goods traffic	Gtkm	21	1639.2	189.8	1288.7	1925
Rail goods traffic	Gtkm	21	406.5	21.3	363.5	452
Inland waterways goods traffic	Gtkm	21	137.7	10.5	119.8	155.5
Final consumption residential	Mtoe	21	285.4	11.3	263.7	298.3
Space heating climate corrected	Mtoe	21	209.6	10.1	188.5	221.0
Water heating	Mtoe	21	38.9	0.9	36.7	40.2
Cooking	Mtoe	21	15.1	0.9	13.4	16.3
Lighting	Mtoe	21	5.6	0.6	4.6	6.2
Large appliances	Mtoe	21	16.1	0.3	15.3	16.6
Number of households	k	21	201284.1	10896	183899	216757.9
Floor area of dwellings (average)	m^2	21	88	2.3	84.2	91.4
Stock of dwellings permanently occupied	k	21	197089.4	12442.8	177121.1	214597.5
Stock of large appliances	k	21	537224.9	52505.2	450047.7	614989.6
Final consumption services	Mtoe	21	137.6	13.1	114.3	157.9
Final consumption agriculture	Mtoe	21	26.7	2.5	23.4	31.6

[1] 'Mtoe' - Million tons of oil equivalent; 'Gpkm' - Gigapassenger-kilometre or 10^9 passenger-kilometre; 'Gtkm' - Gigatonne-kilometre or 10^9 tonne-kilometre; 'k' - Thousand; 'm^2' - Square meters; 'KD' - Constant 2010 US$; '$MtCO_2$' - Million tonnes of carbon dioxide.

Gross value added	KD	21	1.42E+13	1.47E+12	1.14E+13	1.61E+13
Services value added	KD	21	1.03E+13	1.22E+12	8.01E+12	1.19E+13
Agriculture value added	KD	21	2.45E+11	96814975	2.23E+11	2.62E+11
Industry value added	KD	21	3.68E+12	2.54E+11	3.22E+12	4.10E+12
Total CO_2 emissions	$MtCO_2$	21	3550.8	230.3	3043.6	3772.5
Industry	$MtCO_2$	21	1123	143.2	879.3	1297.2
Transport	$MtCO_2$	21	941.4	40.6	859.0	1007.6
Residential	$MtCO_2$	21	855.3	70.3	685.0	966.2
Services	$MtCO_2$	21	528.3	33.1	479.5	580.3
Agriculture	$MtCO_2$	21	102.8	6.6	91.9	116
Energy dependence	%	21	50	3.9	43.1	54.5

Table 1. Descriptive statistics.

The Logarithmic Mean Divisia Index I (LMDI-I) decomposition approach is employed to estimate the level of energy efficiency improvements in the European Union.

The decomposition analysis separates and quantifies the impacts of individual factors ('effects') associated with the changes in economic activity, structure, and energy intensities on the final energy consumption (Ang 2005; 2015) in each sector of the European Union from 1995 to 2015. The following three main factors were identified in decomposition analysis: (i) activity, which represents basic human or economic actions that drive energy use in a particular sector (e.g., the value-added output in the industrial or service sectors); (ii) structure, which reflects the mixture of activities within a sector that can affect how energy is used (e.g., the share of production represented by each sub-sector of industry); and (iii) intensity, which represents the energy use per unit of activity, such as the ratio between energy consumption and the gross value added in the industrial sector or the ratio between energy consumption and the floor area for space heating in the residential sector.

Table 2 illustrates the data employed in the decomposition analysis. For each sector and/or sub-sector/end-use, an indicator of 'activity', 'structure', and 'intensity' is constructed[2].

[2] Motorcycles and small appliances are excluded from the analysis due to the lack of data reagrding the passenger kilometre for motorcycles and the stock of small appliances.

Sector	Sub-sector/End-use	Activity	Structure	Intensity
Industry	Chemical	Gross value added	Share of value added	Energy/value added
	Primary metals			
	Non-metallic minerals			
	Wood			
	Paper, pulp and printing			
	Food			
	Textile and leather			
	Machinery			
	Transport equipment			
	Mining			
	Construction			
	Other industries			
Transport	**Passenger transport**			
	Cars	Passenger kilometre	Share of passenger-kilometres	Energy/passenger-kilometre
	Buses		Share of passenger-kilometres	Energy/passenger-kilometre
	Rail passenger transport		Share of passenger-kilometres	Energy/passenger-kilometre
	Domestic air transport		Share of passenger-kilometres	Energy/passenger-kilometre
	Freight transport			
	Trucks and light vehicles	Tonne kilometre	Share of tonne-kilometres	Energy/tonne-kilometre
	Rail goods transport		Share of tonne-kilometres	Energy/tonne-kilometre
	Waterways goods transport		Share of tonne-kilometres	Energy/tonne-kilometre
Residential	Space heating climate corrected	Households	Floor area/households	Energy/floor area
	Water heating		Occupied dwellings/households	Energy/occupied dwelling
	Cooking		Occupied dwellings/households	Energy/occupied dwelling
	Lighting		Floor area/households	Energy/floor area
	Large appliances		Appliance stock/households	Energy/appliance unit
Services	Services	Gross value added	Share of value added	Energy/value added
Agriculture	Agriculture	Gross value added	Share of value added	Energy/value added

Table 2. Data and indicators included in the LMDI-I analysis.

Among the recently developed decomposition methods, the Logarithmic Mean Divisia Index in the additive form (LMDI-I) had several advantages (Ang 2004; 2005; 2015; Ang et al. 2009; Ang and Wang 2015) and is, therefore, used in this study (for further discussion regarding these advantages, please see Section 2).

Assuming that V is an aggregate composed of n factors $(x_1, x_2, \dots, x_n)$ and that from period 0 to T the aggregate changes from V^0 to V^T, the objective is to derive the contributions of n factors to the change in the aggregate, which can be expressed as follows:

$$\Delta V_{tot}=V^t-V^0=\Delta V_{x_1}+\Delta V_{x_2}+...+\Delta V_{x_n} \tag{1}$$

$$\Delta V_{x_k}=\sum L\,(V_i^t, V_i^0)\ \ln\left(\frac{x_{k,i}^T}{x_{k,i}^0}\right)$$

where i indicates the five sectors (industry, transport, residential, services, and agriculture), k indicates the explanatory factors (activity, structure, and intensity) and $L(a, b) = (a - b)/(\ln a - \ln b)$ is the logarithmic mean of two positive numbers, i.e., a and b, which in this case, are the aggregates of the final energy consumption during years 0 and T that are used as the weighting function in LMDI-I (additive form).

The IDA identity can be expressed as follows:

$$E=\sum_i E_i=\sum_i Q\ \frac{Q_i}{Q}\ \frac{E_i}{Q_i}=\sum_i Q\, S_i I_i \tag{2}$$

where E is the total energy consumption, Q is the overall activity level, E_i is the energy consumption in sector i, Q_i is the activity level in sector i, S_i is the structure (activity share) of sector i, and I_i is the energy intensity in sector i.

The three explanatory effects in the additive form are calculated as follows:

Activity effect:

$$\Delta E_{act}=\sum_i L(E_i^T, E_i^0)\ln\left(\frac{Q^t}{Q^0}\right) \tag{3}$$

Structure effect:

$$\Delta E_{str}=\sum_i L(E_i^T, E_i^0)\ln\left(\frac{S_i^t}{S_i^0}\right) \tag{4}$$

Intensity effect: $$\Delta E_{int} = \sum_i L(E_i^T, E_i^0) \ln\left(\frac{I_i^t}{I_0^t}\right) \tag{5}$$

To analyse the drivers of the energy consumption changes in more detail, for the industrial, freight transport, passenger transport, and residential sectors, the LMDI-I analysis is conducted at the sub-sector/end-use level. The aggregate industrial, freight transport, passenger transport, and residential final energy consumption changes are given by the sum of the changes in their sub-sectors or end-uses[3] as follows:

$$\sum_j \Delta E_{tot}^j = \sum_j \Delta E_{act}^j + \sum_j \Delta E_{str}^j + \sum_j \Delta E_{int}^j \tag{6}$$

where *j* indicates the twelve sub-sectors of the industrial sector (chemical, primary metals, non-metallic minerals, wood, paper, pulp and printing, food, textile and leather, machinery, transport equipment, mining, construction, and other industries), the four sub-sectors of the passenger transport sector (cars, buses, rail passenger transport, and domestic air transport), the three sub-sectors of the freight transport sector (trucks and light vehicles, rail goods transport, and waterway goods traffic), and the five end-uses of the residential sector (space heating, water heating, cooking, lighting, and large appliances).

Then, the isolated energy intensity changes in each sector (e.g., industry, or residential) and sub-sector/end-use (e.g., chemical industry, or space heating) can be used as a proxy of energy efficiency improvements. Although it is impossible to observe the physical quantities that define 'efficiency' in the engineering sense, by building from the disaggregated data and incorporating the changes in other explanatory factors, the measures of intensity more closely approximate the changes in the underlying efficiency of energy use (Xu and Ang 2014; Goh and Ang 2018). Differing from *ex ante* engineering

[3] The decomposition is perfect and there is no residual at the aggregate (single-step procedure) and subcategory (step-by-step procedure) levels.

estimates, these *ex post* estimates of energy savings account for potential rebound effects and other behavioural responses or implementation challenges that typically reduce the expected energy savings from energy efficiency improvements (Sorrell 2007; Fowlie et al. 2018; Gillingham et al. 2018; Valentová et al. 2018).

The difference between the total energy consumption in *T* and the total energy consumption in 0 is equal to the sum of the three effects (no residual) as follows:

$$E^{t}-E^{0}=\Delta E_{tot}=\Delta E_{act}+\Delta E_{str}+\Delta E_{int} \tag{7}$$

Given the availability of balanced time-series data, chaining decomposition is preferred over non-chaining decomposition. The advantage of a chaining analysis is that the results reflect year-to-year changes. This analysis also fully uses the data and is more flexible in terms of application.

To track the progress towards the efficiency target established for 2030, the estimated energy efficiency improvements from 2005 to 2015 are compared to the historical 2005 final energy consumption levels. Consistent with other climate and energy targets, the European Commission, the European Parliament and the Council of the European Union translated the PRIMES projected energy reduction target into a reduction target compared to 2005 as the reference year for energy efficiency. Specifically, to achieve the energy efficiency target established for 2030 the final energy consumption needs to be approximately 20% lower than the historical final energy consumption in 2005 (The European Parliament and the Council of the European Union 2018, Directive (EU) 2018/2002).

Finally, to better understand the role played by energy efficiency in increasing the levels of energy security, a gross inland energy consumption[4] coefficient is constructed. This coefficient is the result of

[4] 'Gross inland energy consumption' (GIC) is the total energy demand in a country or region. GIC represents the quantity of energy necessary to satisfy the inland consumption of the geographical entity under consideration. GIC covers consumption by the energy sector (primary energy), the final energy consumption by end users, distribution and transformation losses, and the energy consumed for purposes other than producing useful energy.

the ratio of the total gross inland energy consumption to the final energy consumption of the EU during the period 1995–2015 as follows:

$$\beta_t = \frac{E_{g,t}}{E_{f,t}} \tag{8}$$

where β_t is the yearly gross inland energy coefficient, and $E_{g,t}$ and $E_{f,t}$ are the gross inland and final energy consumption levels of the EU on a yearly basis (t=1996, 1997…2015), respectively.

Then, the yearly gross inland energy coefficient is multiplied by the annual amount (Mtoe) of energy saved due to energy efficiency improvements ($\overline{Eff_t}$) to obtain an estimate of the yearly average gross inland energy saved ($\overline{E_{gsav,t}}$) as follows:

$$\overline{E_{gsav,t}} = \beta_t * \overline{Eff_t} \tag{9}$$

Then, the notional percentage variation in energy dependence from 1995 to 2015 in the absence of energy efficiency improvements $\overline{\%E_{d,t}}$, is estimated as follows:

$$\overline{\%E_{d,t}} = \frac{(MtE_{d,t} - \overline{E_{gsav,t}})}{E_{g,t}} *(100) \tag{10}$$

where $MtE_{d,t}$ is the amount of Mtoe imported each year, $\overline{E_{gsav,t}}$ is the yearly average gross inland energy (Mtoe) saved due to energy efficiency improvements, and $E_{g,t}$ is the total (yearly) gross inland energy consumption.

As many European energy importing countries do not have the resource capacity to expand domestic production to meet the increased demand, for simplicity, it is assumed that all gross inland energy that is not saved due to energy efficiency improvements is imported. The results provide an estimate of the hypothetical variation in the EU's energy dependency in case there were no energy efficiency improvements - *ceteris paribus*.

To evaluate the impact of energy efficiency improvements on the emissions of the European Union, a yearly CO_2 emissions coefficient is constructed for each sector. The CO_2 emissions coefficient is multiplied by the amount of energy saved due to energy efficiency improvements (each year) to provide an estimate of the yearly average CO_2 emissions saved. Therefore, $\lambda_{i,t}$, which is the average CO_2 coefficient in sector *i* (industry, transport, services, residential, or agriculture) on a yearly basis *t*, is calculated as follows:

$$\lambda_{i,t}=\frac{\overline{ECO_{2,i,t}}}{\overline{E_{i,t}}} \tag{11}$$

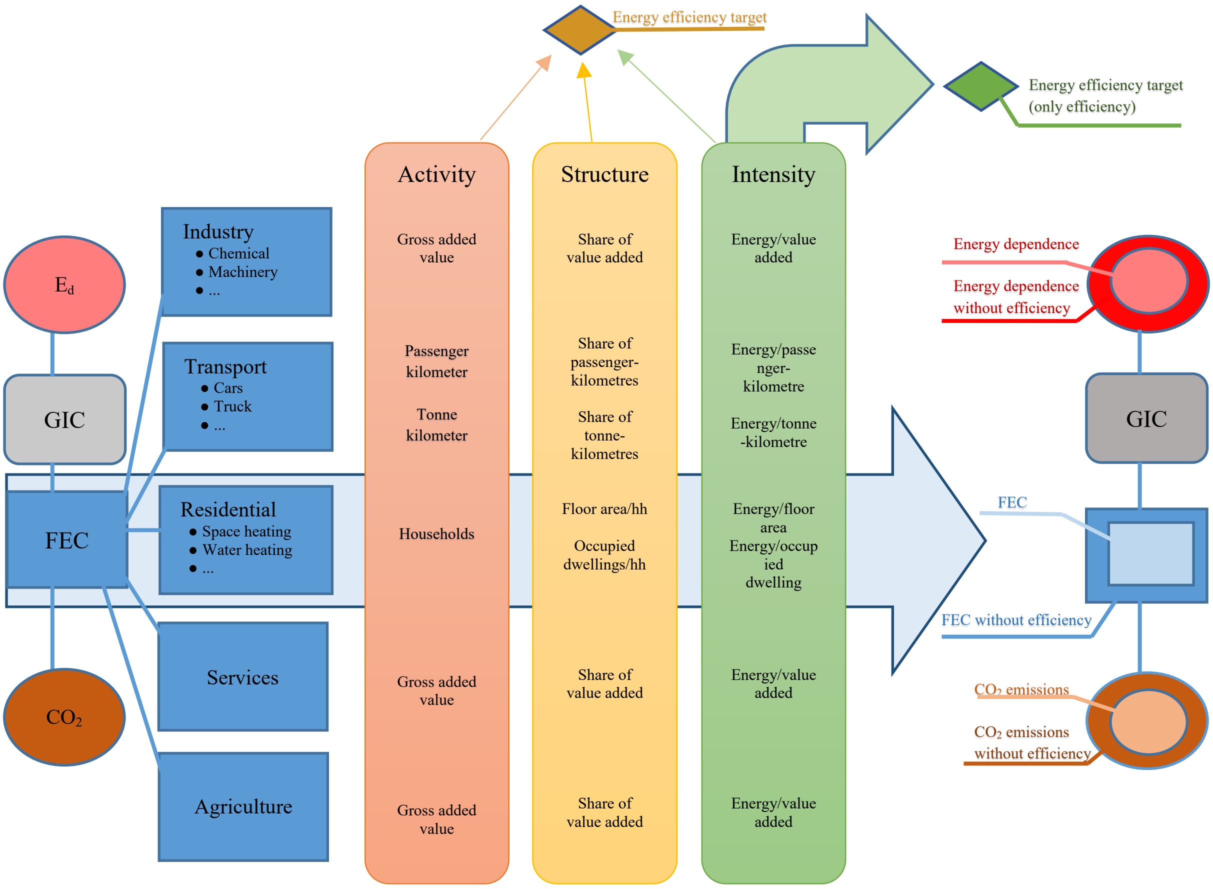
where $\overline{ECO_{2,i,t}}$ represents the average CO_2 emissions in sector *i* and year *t*, and $\overline{E_{i,t}}$ is the energy consumption in sector *i* and year *t*. Then, the yearly average CO_2 emissions coefficient in each sector $\lambda_{i,t}$ is used to estimate the total (yearly) CO_2 emissions saved as follows:

$$CO_2sav_t=\sum_{i=1}^{n}(\lambda_{i,t}*\overline{Eff_{i,t}}) \tag{12}$$

where $\overline{Eff_{i,t}}$ is the amount of energy saved due to energy efficiency improvements (each year) in sector *i*, and CO_2sav_t is the total amount of CO_2 not emitted on a yearly basis in all the sectors (*n* =5) due to energy efficiency improvements.

Figure 1 provides a simplified graphical representation of the data and methods.

Figure 1. Simplified graphical representation of the data and methods[5].



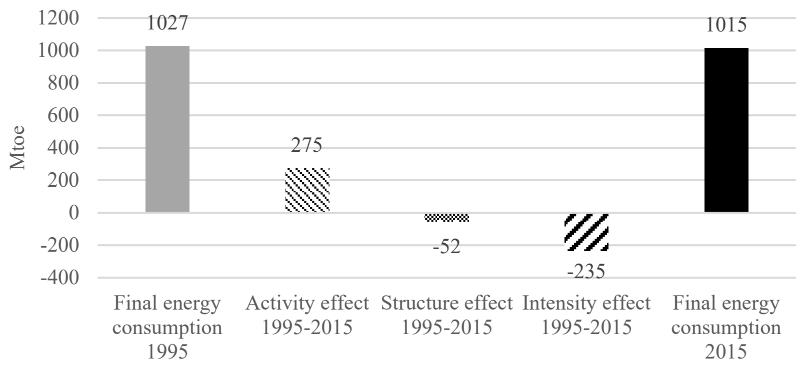
4. Results and discussions

4.1 Variation in final energy consumption

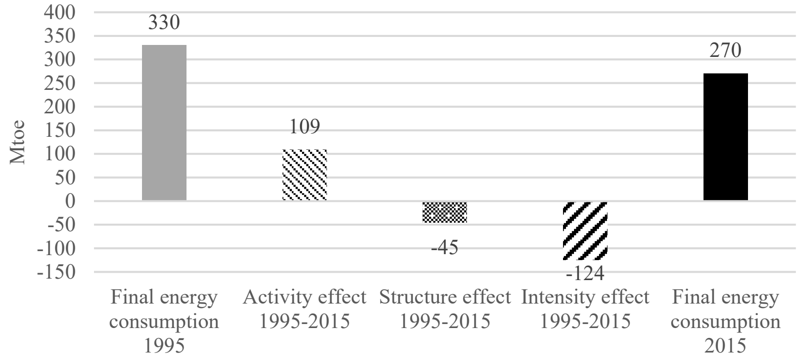
Figure 2 shows the contribution of the 'activity effect', 'structure effect', and 'intensity effect' to the variation in the final energy consumption by all types of end-users and each end-use sector in the European Union over the period 1995–2015 using the LMDI-I decomposition approach.

[5] 'FEC' - Final energy consumption; 'GIC'- Gross inland energy consumption; 'E_d'- Energy dependence; 'CO_2'- Carbon dioxide.

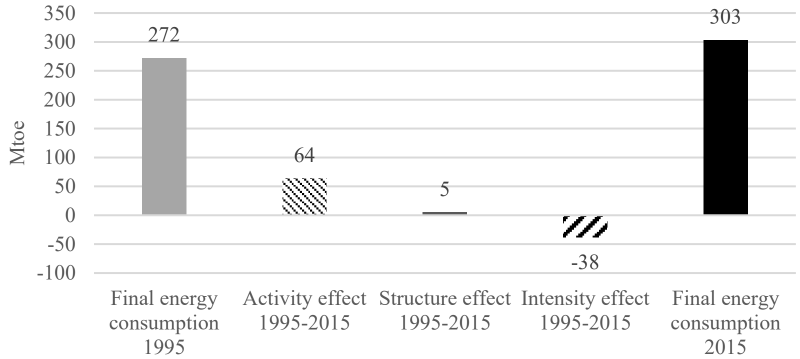
Total



Industry



Transport



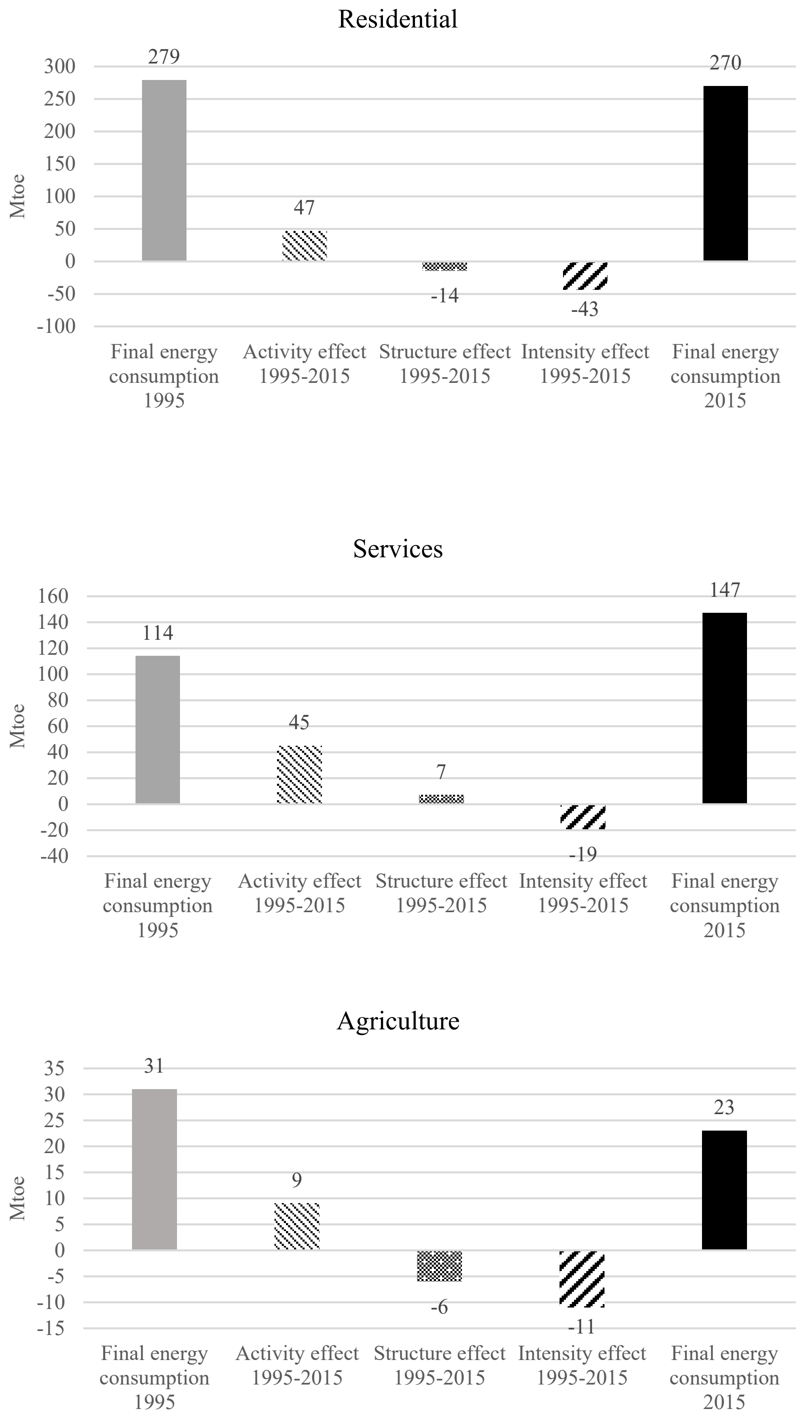


Figure 2. Variation in the final energy consumption in the European Union from 1995 to 2015.

The year-to-year variations in the final energy consumption (Mtoe) by sector and sub-sectors/end-use from 1995 to 2015 due to the 'activity effect', 'structure effect', and 'intensity effect' are shown in the Appendix (Table 3, Table 4, and Table 5).

From 1995 to 2015, the EU final energy consumption decreased by 12 Mtoe, corresponding to a decrease of 1.2%. The decomposition results show that the increase of 275 Mtoe in the final energy consumption caused by activity effects was counterbalanced by intensity (-235 Mtoe) and structural changes (-52 Mtoe). In contrast to the study conducted by Reuter et al. (2019), who investigated the drivers of changes in final energy consumption in the European Union over a shorter period (2000-2015)[6], the energy intensity improvements (alone) have largely (but not completely) offset the increase in the final energy consumption caused by activity effects.

Without the energy intensity improvements that occurred between 1995 and 2015 (while the other factors remained constant), the final energy consumption in 2015 could have been 23.2% higher. The 235 Mtoe saved due to energy intensity improvements corresponds to the final energy consumption in the United Kingdom, Spain, and Austria combined in 2015.

The highest energy reductions due to energy intensity improvements were achieved during the years after the implementation of the following most important pieces of legislation in the energy efficiency domain (Appendix, Table 5): 2007 (Directive 2006/32/EC), 2011 (Directive 2010/30/EU and Directive 2010/31/EU), and 2014 (Directive 2012/27/EU that entered into force on 4 December 2012). In addition, 62% of the total energy intensity improvements between 1995 and 2015 were achieved during the decade 2005–2015. Although it is impossible to show a causal relationship between energy intensity trends and the implemented energy efficiency policies, these results may reflect the growing influence and ambition of the EU action on national energy efficiency strategies.

Consistently with Reuter et al. (2019), more than half of the final energy intensity improvements were driven by the industrial sector. More specifically, the primary metal manufacturing sub-sector was responsible for 32.5% of the energy saved in the industrial sector between 1995 and 2015, followed by the chemical (16.9%), non-metallic minerals (15.1%), other/miscellaneous (12.2%), textile and leather (6.4%), food (6.1%), machinery (5.2%), paper, pulp and printing (3.4%), transport equipment (1.3%), mining (1.1%), and construction (0.9%) industries. The wood industry was the only industrial sub-

[6] According to Reuter et al. (2019), from 2000 to 2015 the intensity effect contributed to a reduction of 210 Mtoe in the EU final energy, counteracting the increase in final energy due to activity effects (125 Mtoe).

sector that did not decrease its final energy intensity. A structural shift towards less intensive industrial sub-sectors and more service-based economies resulted in a decrease of 45 Mtoe. Energy-intensive industries such as the chemical and primary metal industries, decreased their final energy consumption by 15% and 30%, respectively, and the contribution of the industry value added to the economy decreased by 3.8%. Overall, economic activity increased energy consumption by 109 Mtoe; however, the impact of the economic recession in 2008–2009 was captured by the negative activity effect of 12.9 Mtoe in 2009 (Appendix, Table 3).

Regarding the transport sector (both passenger and freight transport), the final energy consumption increased by 11.4%. The increase of 64 Mtoe and 5 Mtoe, which was attributed to activity and structural effects, respectively, was only partially offset by intensity improvements (-38 Mtoe). Overall, 63.5% of the final energy intensity improvements were driven by passenger transport, while the remaining improvements were driven by freight transport. From 1995 to 2015, cars accounted for 90% of the intensity improvements in the passenger transport sector, whereas trucks and light vehicles represented 66.2% of the intensity improvements in freight transport, followed by waterways goods traffic (21.4%), and rail goods transport (12.4%). However, from 1995 to 2015 the final energy consumption of heavy-duty and light vehicles and the road traffic of goods increased by 27.3% and 37.3%, respectively. Differently from new passenger cars and light commercial vehicles, which are subject to emission performance standards (Regulation (EC) No. 443/2009; Regulation (EU) No. 510/2011), the emissions of new heavy-duty vehicles in the European Union have not been regulated[7] so far, making Europe the largest market without mandatory limits for such vehicles (Delgado and Gonzalez 2018). This lack of regulation, combined with the possibility of the EU Member States to exclude the energy consumption of the transport sector from the baseline used for setting the mandatory energy-saving target (Article 7 of the Energy Efficiency Directive 2012/27/EU and the revised Energy Efficiency Directive

[7] In May 2018, the European Commission presented a legislative proposal setting the first-ever CO_2 emission standards for heavy-duty vehicles in the EU. The proposal establishes an indicative reduction target of 15% in 2025 and at least of 30% in 2030 compared to 2019 average CO_2 emission levels (European Commission 2018).

2018/2002), may contribute to explain the relative small energy efficiency gains obtained in the transport sector (especially freight transport).

The final residential energy consumption decreased by 3.2% over the period 1995–2015. An increase in the number of households (17.9%) and, consequently, in the household equipment ownership resulted in an increase of 47 Mtoe (activity effect). However, energy intensity improvements and structural effects contributed to a reduction of 43 and 14 Mtoe, respectively. Space heating was the end-use sector that registered the largest energy intensity improvements, leading to a reduction of 25 Mtoe, followed by water heating (-9.2 Mtoe), large appliances (-6 Mtoe), lighting (-1.46 Mtoe), and cooking (-1.43 Mtoe). In addition to more efficient heating systems, the improvements in space heating consumption can be ascribed to the renovation and construction of new buildings and tighter building codes (Trotta et al. 2018).

Concerning the service sector, the final energy consumption increased by 29% from 1995 to 2015. The moderate positive effects of energy intensity improvements (-19 Mtoe) were counteracted by a 45 and 7 Mtoe increase due to activity and structural effects, respectively. Consistent with Marrero and Ramos-Real (2013) and Obadi and Korček (2015), the growth and importance of the service sector in the EU economy[8] did not lead to corresponding energy efficiency improvements.

Finally, the reduction in the final energy consumption in agriculture by 25.8% was mainly driven by energy intensity improvements (-11 Mtoe) and, to a lesser extent, structural effects (-6 Mtoe), while activity effects led to an increase of 9 Mtoe.

4.2 Energy efficiency improvements

Figure 3 illustrates (i) the actual variation in the final energy consumption in the European Union from 2005 to 2015; (ii) the hypothetical variation in the final energy consumption due to energy intensity

[8] From 1995 to 2015, the contribution of the services valued added to the economy increased by 3.8%.

(hereafter referred to as 'energy efficiency') improvements alone; and (iii) the energy efficiency target for 2030 compared to the historical 2005 final energy consumption levels (-20%).

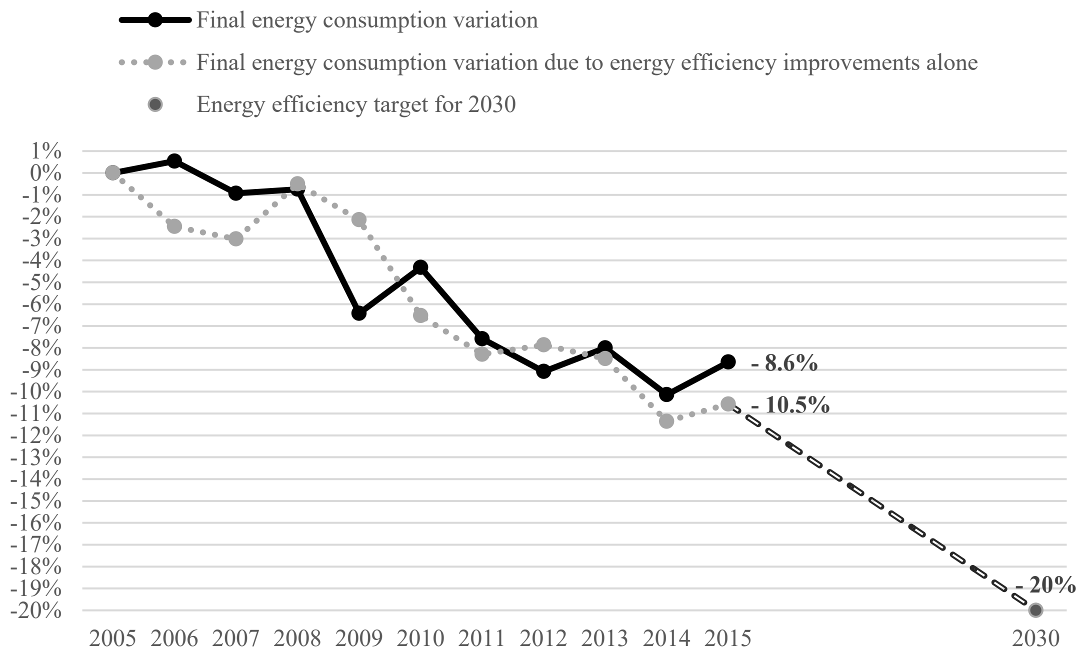


Figure 3. Energy efficiency target for 2030 compared to energy efficiency improvements using LMDI-I (2005-2015).

Although the 32.5% energy efficiency target for 2030 is commonly discussed in terms of the change in primary energy consumption in 2030 compared to the 2007 PRIMES baseline projections (percentage of target to be achieved), in the revised Energy Efficiency Directive (EU) 2018/2002, the European Commission, the European Parliament and the Council of the European Union translated this target into a reduction target compared to the historical 2005 energy consumption levels. This comparison facilitates the assessment of the target, improves its transparency, and makes it consistent with other climate and energy targets. This target corresponds to a 26% reduction in primary energy consumption compared to the historical 2005 primary energy consumption levels, and a 20% reduction in final energy consumption (compared to the historical 2005 final energy consumption levels). The contribution of each sector to the reduction of 20% in the final energy consumption (compared to the historical 2005 final energy consumption levels) could be as follows: a 19.9% reduction in the final energy consumption of the industrial sector compared to the 2005 levels, a 26.9% reduction in the final energy consumption of the residential sector, a 22.5% reduction in the final energy consumption of the tertiary sector, and a 12.3% reduction in the final energy consumption of the transport sector[9].

From 2005 to 2015, the final energy consumption decreased by approximately 8.6%. However, when energy efficiency improvements are disentangled from the other factors influencing the variation in final energy consumption (activity and structural changes), the results show that the final energy consumption in 2015 could have been 10.5% lower than the consumption levels in 2005.

Between 2005 and 2015, energy efficiency improvements alone saved 145 Mtoe and contributed to an average annual consumption reduction of 1.05%. In total, 44.2% of the energy savings were driven by the industrial sector, followed by the residential sector (27.7%), the transport sector (13.8%), the service sector (10.8%), and the agricultural sector (3.5%). These results are lower than the estimates provided by a recent JRC report (Economidou 2017) in which energy efficiency in the EU between 2005 and 2015 contributed the saving of 169.9 Mtoe mainly due to improvements in the commercial (57%) and residential (39.5%) sectors and only marginal improvements in the transport sector (3.5%).

When the energy efficiency target for 2030 is assessed as the variation in final energy consumption due to energy efficiency improvements alone (and not other factors, such as economic activity, population, and economic structure, i.e., the EU means of assessment), the results indicate that 52.5% of the target for 2030 has already been achieved in 2015. Continuing this line of inquiry at the sectoral level, the energy saved due to energy efficiency improvements in industry from 2005 to 2015 achieved 98.5% of the target for 2030, whereas 51.3% of the target was achieved in the transport sector, 50.6% of the target was achieved in the residential sector, and 48.3% of the target was achieved in the service sector. In addition, at a constant annual contribution of energy efficiency to the reduction in final energy consumption of 1.05%, the remaining gap towards 2030 could be closed by the end of 2024.

[9] These calculations are based on the methodology used by the EC (European Commission 2016b) to determine the contribution of each sector to the final energy consumption reduction (compared to the historical 2005 final energy consumption levels) in different scenarios.

4.3 Energy security and climate benefits

Figure 4 illustrates (i) the actual energy dependence level (%) of the EU from 1995 to 2015; (ii) the notional variation in energy dependence per year in the absence of energy efficiency improvements; and (iii) the notional energy dependence level in 2015 without the energy efficiency improvements that occurred between 1995 to 2015 (*ceteris paribus*). The detailed results are provided in the Appendix (Table 6).

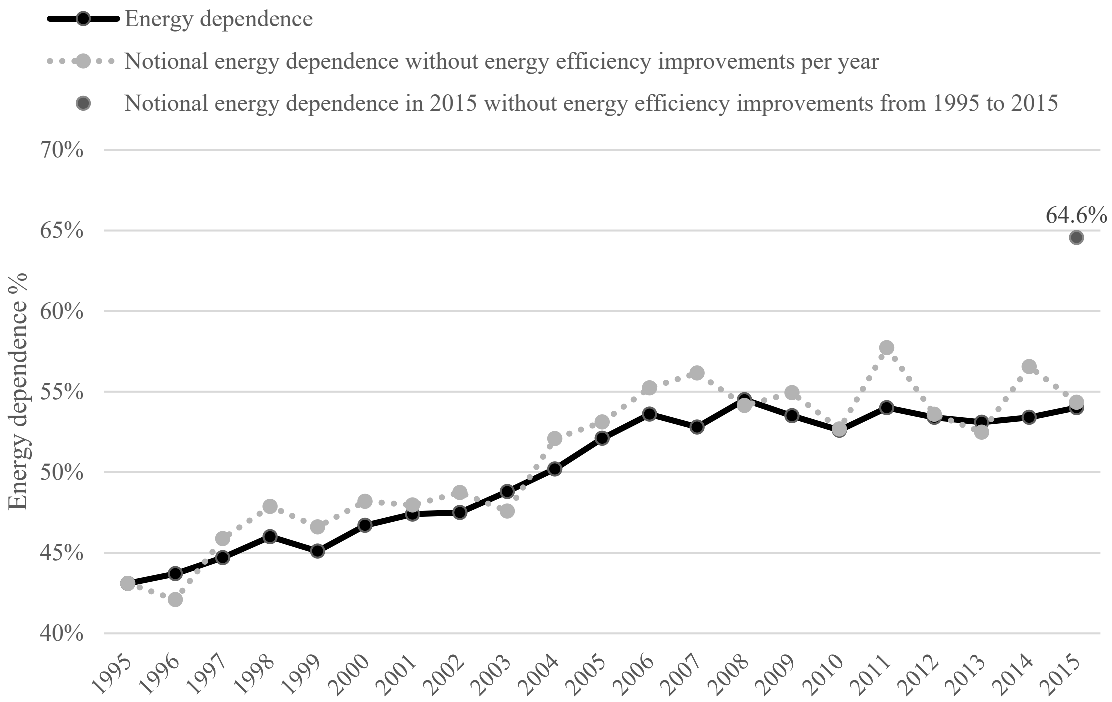


Figure 4. Energy security benefits due to energy efficiency improvements (1995-2015).

In 2015, the EU imported 54% of the energy it consumed; such energy import dependency increased by 25.3% over the period 1995–2015. Without the energy efficiency improvements that occurred between 1995 and 2015, the EU energy dependence on imports in 2015 could have hypothetically been 64.6%, corresponding to an increase of 12.6% in the actual levels of energy dependence - *ceteris paribus*. In total, energy efficiency contributed to saving 361 Mtoe of gross inland energy and reduced the energy dependency at an average rate of approximately 1% per year. The gross inland energy saved due to energy efficiency improvements between 1995 and 2015 corresponds to the energy imported from Russia and Norway, which are among the principal suppliers of the EU energy imports[10], and 22.1% of the total gross inland energy consumption in 2015.

Figure 5 depicts (i) the EU's total CO_2 emissions ($MtCO_2$) from 1995 to 2015; (ii) the notional variation in the total CO_2 emissions per year in the absence of energy efficiency improvements; and (iii) the notional amount of CO_2 emissions in 2015 without the energy efficiency improvements that occurred between 1995 and 2015 (*ceteris paribus*). The detailed results are provided in the Appendix (Table 7).

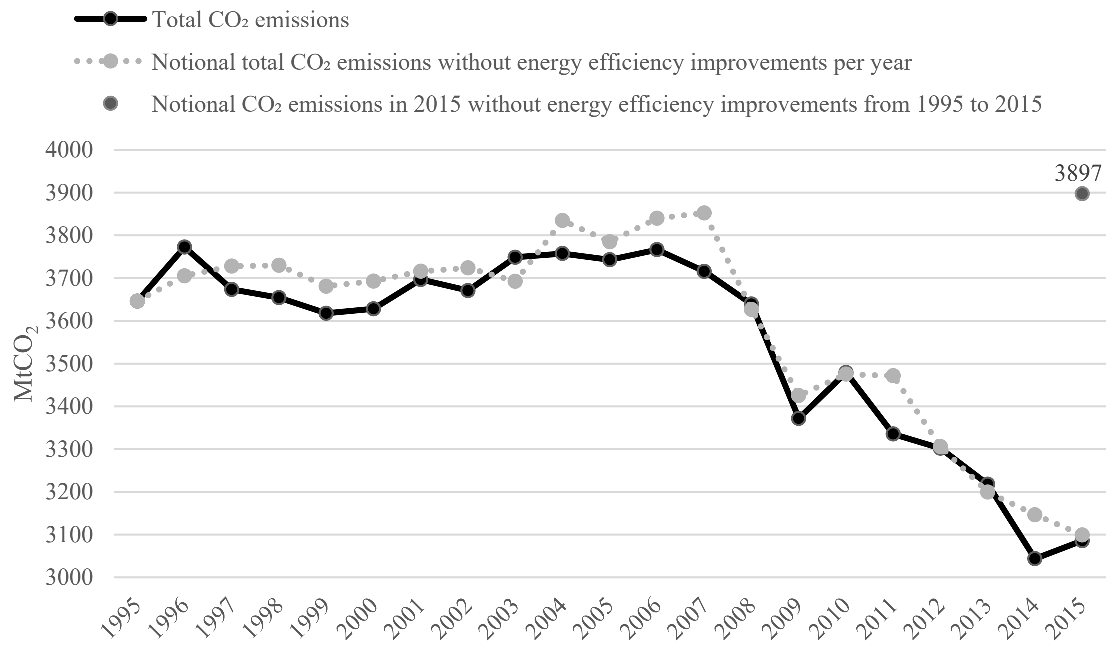


Figure 5. CO_2 emissions reduction due to energy efficiency improvements (1995-2015).

The CO_2 emissions resulting from the EU's energy consumption from 1995 to 2015 decreased by 15.4%. From 1995 to 2015, energy efficiency contributed to a reduction of 811 $MtCO_2$, corresponding to the total CO_2 emissions in Germany, Greece, and Finland combined in 2015. Without the energy efficiency

[10] In 2015, 29.4% of the EU imports of natural gas, 27.7% of the EU imports of crude oil, and 25.8% of the EU imports of solid fuels were obtained from Russia, whereas 25.9% of the EU imports of natural gas and 11.4% of the EU imports of crude oil were obtained from Norway (Eurostat 2018b; 2018c; 2018d). The amount of these imported sources combined is 360.3 Mtoe.

improvements that occurred between 1995 and 2015, the CO_2 emissions in 2015 could have been 26.3% higher (*ceteris paribus*). Approximately 55.2% of the total CO_2 emissions reduction due to energy efficiency was derived from the industrial sector, 15.4% was derived from the residential sector, 14.5% was derived from the transport sector, 9.4% was derived from the service sector, and 5.3% was derived from the agricultural sector.

The key role of energy efficiency in reducing CO_2 and other greenhouse gas emissions (GHGs)[11] becomes more visible when the results are assessed against the EU climate targets. By 2030, the EU aims to reduce its total greenhouse gas emissions (GHGs) by 40% compared to the 1990 levels. In absolute terms, to achieve this goal, the total GHGs in 2030 should be 3429.82 $MtCO_2e$[12], corresponding to a reduction of 2286.54 $MtCO_2e$ compared to the GHGs in 1990 (5716.36 $MtCO_2e$). In addition, the roadmap for transitioning to a competitive low-carbon economy in 2050 suggests that by 2050, the EU should reduce its GHGs to (at least) 80% below the 1990 levels (European Commission 2011); in absolute terms, this corresponds to a reduction of 4573.088 $MtCO_2e$ compared to the 1990 levels.

Thus, the reduction of 811 $MtCO_2$ as a result of the energy efficiency improvements that occurred from 1995 to 2015 contributed to achieving 35.5% of the climate target established for 2030 and 17.7% of the climate target established for 2050.

[11] The 'Greenhouse gases' (GHGs) include: CO_2 (carbon dioxide), N_2O (nitrous oxide) in CO_2 equivalent, CH_4 (methane) in CO_2 equivalent, HFCs (hydrofluorocarbons) in CO_2 equivalent, PFCs (perfluorocarbons) in CO_2 equivalent, SF6 (sulfur hexafluoride) in CO_2 equivalent, and NF3 (nitrogen trifluoride) in CO_2 equivalent.

[12] 'CO_2e' or 'Carbon dioxide equivalent' is a term used to describe different greenhouse gases in a common unit. For any quantity and type of greenhouse gas, CO_2e is the amount of CO_2 that could have the equivalent global warming impact. This term allows "bundles" of greenhouse gases to be expressed as a single number and different bundles of GHGs to be easily compared (Brander and Davis 2012).

5. Conclusions and implications

On December 11, 2018, the European Parliament and the Council set a binding 32.5% energy efficiency target for 2030 (Directive (EU) 2018/2002). The achievement of this target will determine the success of EU Member States' actions and policy measures to improve energy efficiency and contribute to reducing energy dependence and CO_2 emissions. However, the energy efficiency target is based on a hypothetical percentage of future primary energy use based on an outdated projection that does not account for the different factors influencing the variation in energy consumption and the recent evolution of EU policies.

This study identifies and quantifies the factors influencing the variation in final energy consumption in the EU from 1995 to 2015 by a employing decomposition analysis (LMDI-I) and using disaggregated data. Specifically, the decomposition analysis shows the extent to which the reduction in the EU final energy consumption was driven by energy efficiency improvements, which would otherwise be masked by changes in economic activity and structure. In addition, to track progress towards the 32.5% energy efficiency target, the estimated energy efficiency improvements from 2005 to 2015 are compared to the 2005 historical final energy consumption levels. Finally, to account for economy-wide benefits, the calculated amount of energy savings due to energy efficiency improvements is translated into a reduction in energy dependence and CO_2 emissions.

The results show that from 1995 to 2015, the increase of 275 Mtoe in final energy consumption caused by activity effects was offset by structural changes (-52 Mtoe), especially energy efficiency improvements (-235 Mtoe). At the sectoral level, 52.8% of the energy savings due to energy efficiency improvements were derived from industry, 18.3% were derived from the residential sector, 16.2% were derived from transport, 8% were derived from services, and 4.7% were derived from agriculture.

Without the energy efficiency improvements that occurred between 1995 and 2015, the final energy consumption in 2015 could have been 23.2% higher. In contrast to the industrial and residential sectors, the transport and service sectors did not decrease their energy consumption and showed moderate energy efficiency gains from 1995 to 2015. While energy efficiency improvement actions targeting the transport sector, such as vehicle efficiency standards, fuel tax, training and information on eco-driving, modal shift and mobility reduction measures should be prioritised in future policymaking but, are limited by the scope of Article 7 of the revised Energy Efficiency Directive (2018/2002). In fact, under (extended) Article 7, which requires Member States to set an energy efficiency target for the period 2021–2030, the energy consumption of the transport sector can partially or fully be excluded from the calculation of energy savings (The European Parliament and the Council of the European Union 2018). This exclusion undermines the willingness of policy makers to increase their efforts to improve energy efficiency in the transport sector as confirmed by a recent study analysing the implementation of the Article 7 in EU Member States (Rosenow and Fawcett, 2016); thus far, the experience has shown that all EU Member States, except for Sweden, have excluded the transport sector from the baseline used to establish the target.

Regarding the service sector, its high level of heterogeneity and the lack of disaggregated data at the EU level do not support sound conclusions. As noted by Marrero and Ramos-Real (2013), one possible explanation for the low-energy efficiency gains in the service sector can be attributed to its low degree of competition from abroad, which contrasts the high degree of competition in industry among European countries.

If the energy efficiency target for 2030 is assessed against the variation in final energy consumption due to energy efficiency improvements alone (and not other factors), there are considerable opportunities for its achievement several years before 2030. In fact, the results indicate that the energy savings driven by energy efficiency improvements alone between 2005 and 2015 contributed to achieving 52.5% of the target established for 2030. From this perspective, the 32.5% energy efficiency target appears to be significantly behind that achievable by the EU.

The need for a higher target becomes even more crucial when the benefits of energy efficiency are measured in terms of the security of supply and emission reductions. Hypothetically, the gross inland energy saved (361 Mtoe) due to energy efficiency improvements from 1995 to 2015 could have allowed the EU to not rely on imports from Russia and Norway in 2015. In addition, the energy efficiency improvements from 1995 to 2015 lowered CO_2 emissions in 2015 by 26.3% and contributed to achieving 35.5% of the climate target established for 2030.

Given the key role of energy efficiency in reducing energy consumption, energy dependence, and CO_2 emissions, the declared intention of energy efficiency 'first' as the guiding principle for energy policy making should be more consistently aligned with actual policy implementation and strategic direction. Although it is the responsibilities of the EU Member States to establish concrete measures to improve energy efficiency and achieve the agreed objectives, the crucial role of the EU as stimulus to increase energy efficiency and establish a common framework for mutually reinforcing mechanisms is confirmed by the empirical results. During the period of investigation (1995–2015), the year after the implementation of the most important acts regarding energy efficiency (2007, 2011, and 2014), i.e., Directive 2006/32/EC, Directive 2010/30/EU, Directive 2010/31/EU, and Directive 2012/27/EU (which entered into force on December 4, 2012), registered the highest energy reductions driven by energy efficiency improvements and the highest levels of contribution of energy efficiency in reducing energy dependence and CO_2 emissions.

Therefore, the overall level of the target and its evaluation could influence the level of ambition of energy efficiency policies at the national level and the achievement of energy security and climate change goals. The findings in this study highlight the significant contribution of energy efficiency to reducing energy consumption and the importance of redefining the energy efficiency target in a more consistent way by reconsidering the level to be achieved and evaluating progress accordingly.

Acknowledgements

This work was partially financed by the Jenny and Antti Wihuri Foundation (Jenny ja Antti Wihurin rahasto) under project grant Trotta/00180402, the European Commission under project grant EUFORIE/H2020-EE-2014-2015-RIA/649342, and the Academy of Finland under project grant Kalmi/2700041011. The information and views set out in this article are those of the author and do not reflect those of the funding agencies. The author would like to thank the participants of the 'Energizing Futures – Sustainable Development and Energy in Transition Conference' (June 13–14, 2018) in

Tampere, Sylvia Lorek, and the six anonymous reviewers for their valuable comments on the earlier version of this paper.

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